Technology Development For a Long Duration, Mid-cloud Level Venus Balloon

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Outline

- Background of Venus ballooning
- Overview of JPL-led development effort
- Recent technology development progress
  - FEA analysis of balloon end cap and experimental validation
  - Aerial deployment and inflation flight test
- Conclusions

Background

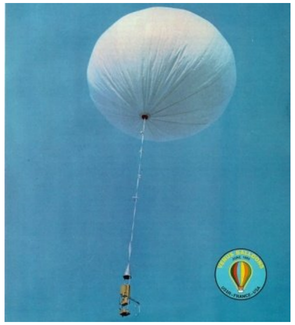
- The Soviet Union successfully flew two balloons at Venus in 1985 as part of the VEGA mission.
  - VEGA-1 on June 11-13
  - VEGA-2 on June 15-17
- These were helium superpressure balloons:
  - 3.4 m diameter
  - 10.5 kg balloon, Teflon-like coated fabric construction
  - 6.7 kg total payload
  - Battery powered for a 2 day lifetime
  - Direct to Earth telecommunications
  - Designed for a 55 km constant altitude but atmospheric winds resulted in a range of 51-55 km
- These missions were successful and returned data on atmospheric winds, cloud particle densities and atmospheric temperature and pressure.

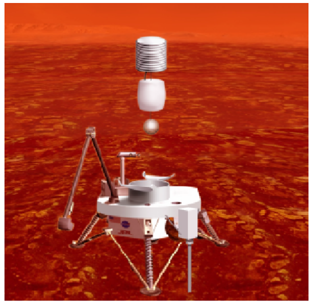
VEGA balloon test flight

Post-VEGA Balloon Options

- Many ideas have emerged for the next balloon mission to Venus:

Flight regime	Environment	Scientific Focus	Technological challenges
> 51 km (VEGA-like)	T < 80 C Sulfuric acid clouds	Meteorology Super-rotation Atmospheric composition	Size scaling from VEGA to accommodate larger payloads. Longer-duration flights (weeks-months)
< 10 km (near-surface)	T > 380 C P > 47 atm	Surface-atmosphere interactions Atmospheric composition	High temp. balloon material (metal?). Refrigeration for payload lifetime > hours
0 > alt > 60 km Altitude cycling	High temperature, high pressure and sulfuric acid	Combined atmosphere and surface investigations.	Phase-change fluid balloons and auxiliary components. High temp balloon material.





- At JPL we have worked on all three concepts in the past 15 years.
- Recent technology development efforts have focused on larger, longer duration VEGA-like balloons for a near-term mission opportunity through the Discovery Program:
  - This kind of balloon can do top priority Venus science.
  - It requires far less technology investment than other kinds of Venus balloon missions.
- The remainder of this talk will describe our work in high altitude (> 51 km) Venus balloons in support of a Discovery proposal called VALOR (PI = Kevin Baines).

VALOR Balloon

- Helium spherical superpressure balloon
  - Sized for 100 kg mass underneath
- Laminate material:
  - Vectran fabric for strength
  - Teflon film for sulfuric acid resistance
  - Second surface aluminum layer for high solar reflectivity
  - Metalized Mylar for helium retention
- Current flight design summarized below:

Metric	Value
Diameter	7.1 m
Surface Area	158 m^2
Volume	187 m^3
Total Balloon Mass	43 kg
Helium Mass	16 kg
Nominal Float Altitude	55.5 km
Payload Mass	100 kg

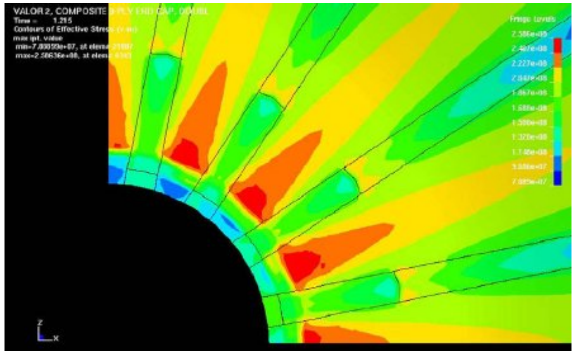
5.5 m diameter prototype testing (2006)

VALOR Balloon Technology Development (2005-2010)

- Current TRL = 5
- Approx. $1M spent 2005-2010
- 2 – 5.5 m prototype balloons built
- 4 – 1 m cylinder balloons built
- Extensive material characterization
- Finite element modeling of balloon stress and deformation
- Sulfuric acid testing of material samples
- Sulfuric acid immersion testing of balloon prototypes
- Long-term (35 day) buoyancy and leak testing
- Laboratory deployment test
- Laboratory inflation test
- Helicopter drop aerial deployment and inflation test
- Results published in Advances in Space Research, 2007 & 2008.

Outdoor heating test

Aerial deployment and inflation test



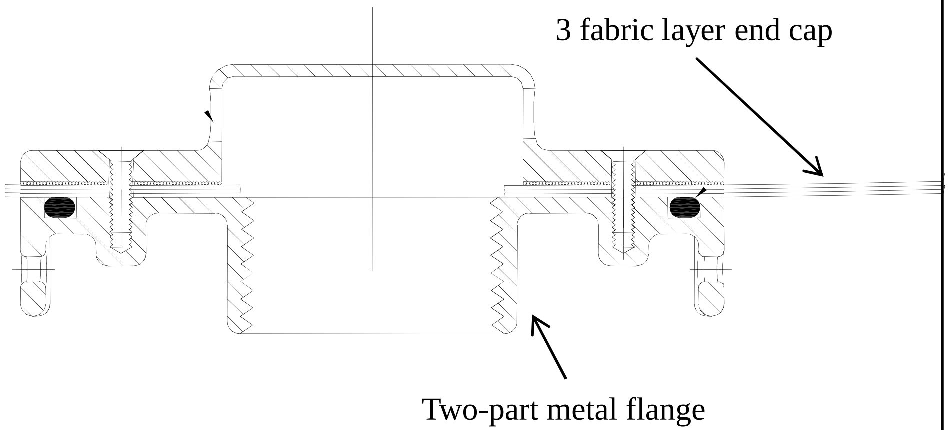
FEA model of balloon end cap

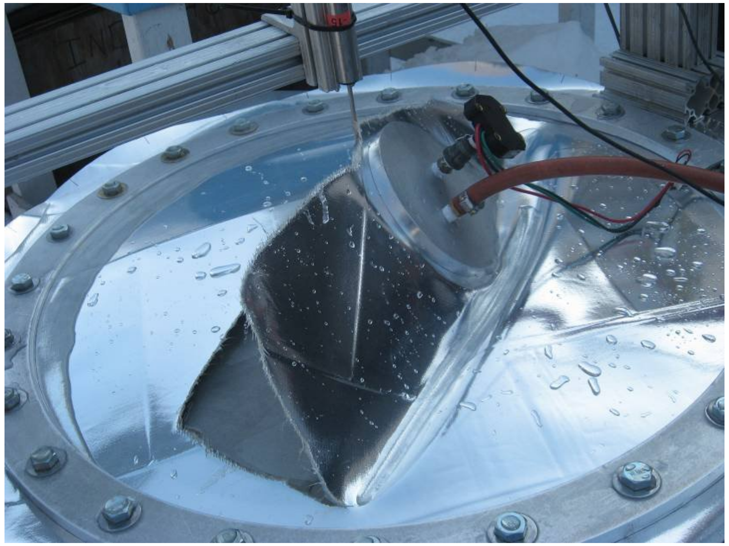
Sulfuric acid testing of material sample

FEA Analysis of Balloon End Cap and Experimental Validation

End Cap Stress Concentration Experiment

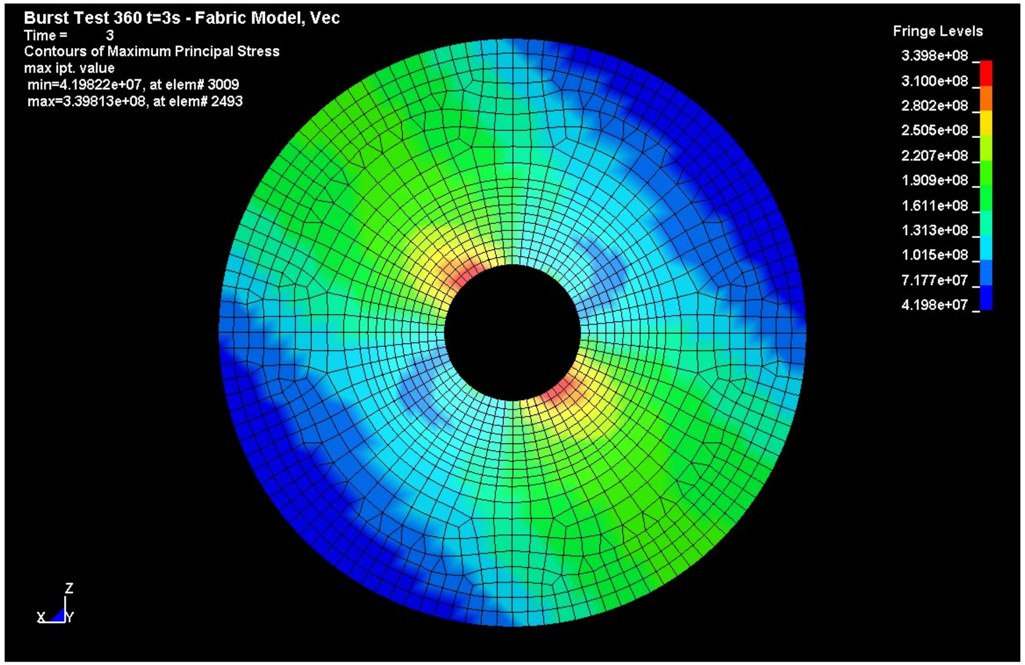
- ILC Dover did an experiment to quantify the stress concentration factor at the junction of the metal balloon end fitting and the reinforced fabric end cap
  - Prior FEA analysis indicated that this was the location where the balloon will fail
- The experiment was done on an end cap replica with d=0.66 m and not on a balloon
- Water pressurization was used to load the test article to failure
  - Deflection as a function of pressure was measured.
- The measured burst pressure was 160 kPa.
  - The material failed at the metal-to-fabric junction, as expected.
- The expected burst pressure based on thin membrane theory (σ=Pr/2t) and material strength characterized in uniaxial pull tests is 250 kPa
- This gives a knock-down factor of 0.64, stress concentration factor of 1.56.





End cap test article after burst

End Cap Stress Concentration FEA Analysis



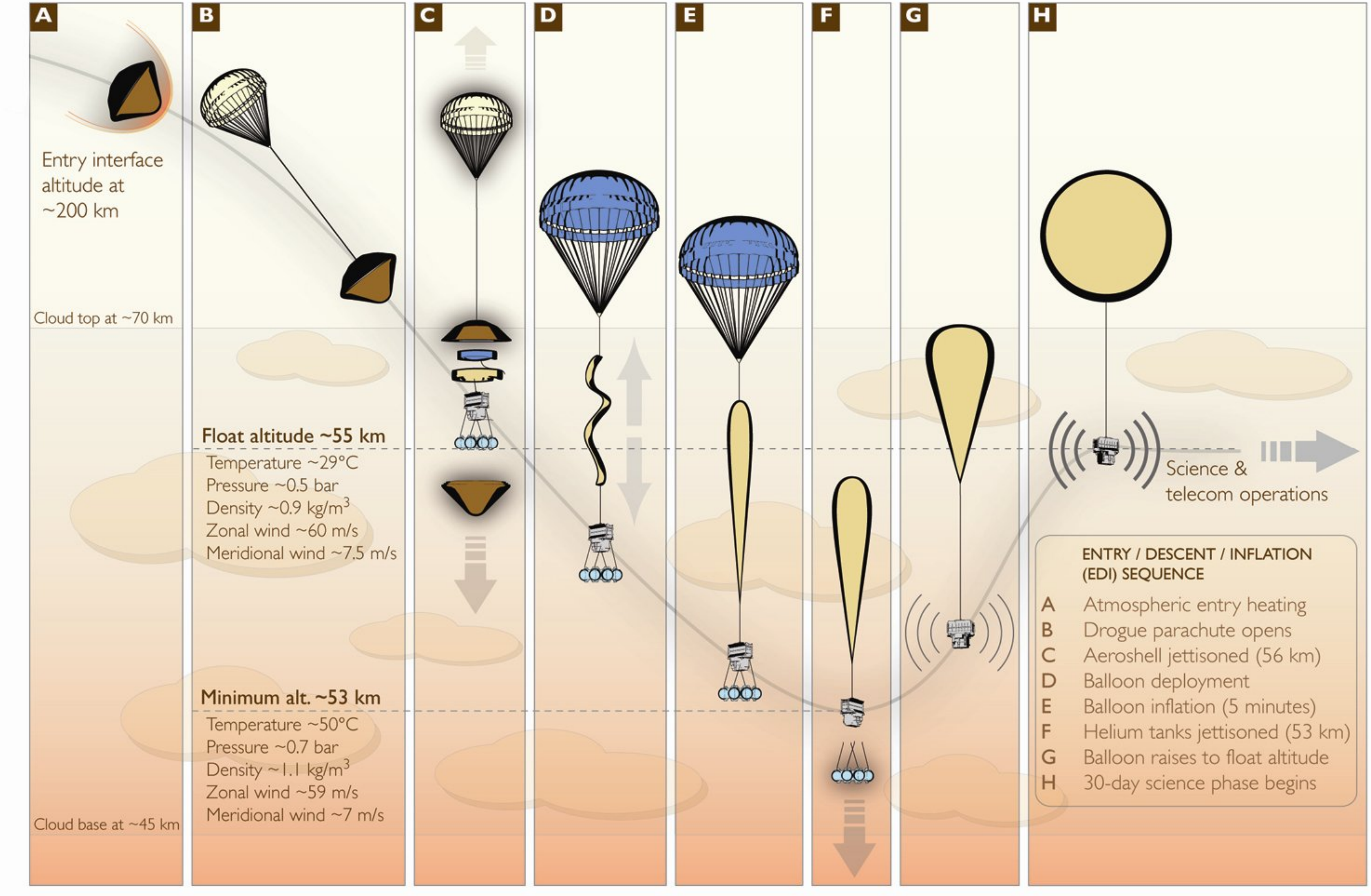
- JPL consultant Shari Day performed finite element analyses on the ILC Dover end cap experiment.
- She constructed a model with LS-DYNA and used membrane elements to represent the 3 layers of balloon material.
  - A non-linear stress-strain curve was used based on existing uniaxial test data of this material.
- The results were:
  - Peak stress at the same point where the test article failed.
  - Failure load of 75 kN/m (σt) on the most stressed of the 3 layers
    - The ILC experiment indicates σt = 75.7 kN/m (thin membrane theory)
    - Separate uniaxial material test data shows a failure load of 71.5 kN/m
  - Deflection at burst = 61 mm
    - c.f. 60.5 mm for the ILC experiment
- Good agreement between FEA and experiment, confirmation of stress concentration factor.

Aerial Deployment and Inflation Flight Test

Test Background

- The VALOR balloon is too large to fit inside either the launch vehicle fairing or the aeroshell once inflated.
  - Inflation must be done upon arrival in the Venusian atmosphere.
- We must avoid overheating the balloon and payload by going too low in the atmosphere.
  - This requires an "aerial deployment and inflation process" while descending under a parachute after atmospheric entry. (i.e., not a surface deployment of the balloon).
  - This approach was used successfully by both VEGA balloons.
  - The graphic on the next slide shows the anticipated VALOR sequence at Venus.
- JPL designed, built and flew a VALOR aerial deployment and inflation experiment in October, 2009 to validate the design of this system and identify any unanticipated problems.
  - The test used a 5.5 m diameter prototype balloon.
  - It was conducted in a remote area of the Mojave desert outside of Los Angeles.
  - It involved a team of 10 people in the field, and many more contributed behind the scenes (design, construction, logistics).
- The test was completely successful. The balloon deployed and inflated as expected without detectable damage.

VALOR EDI Sequence

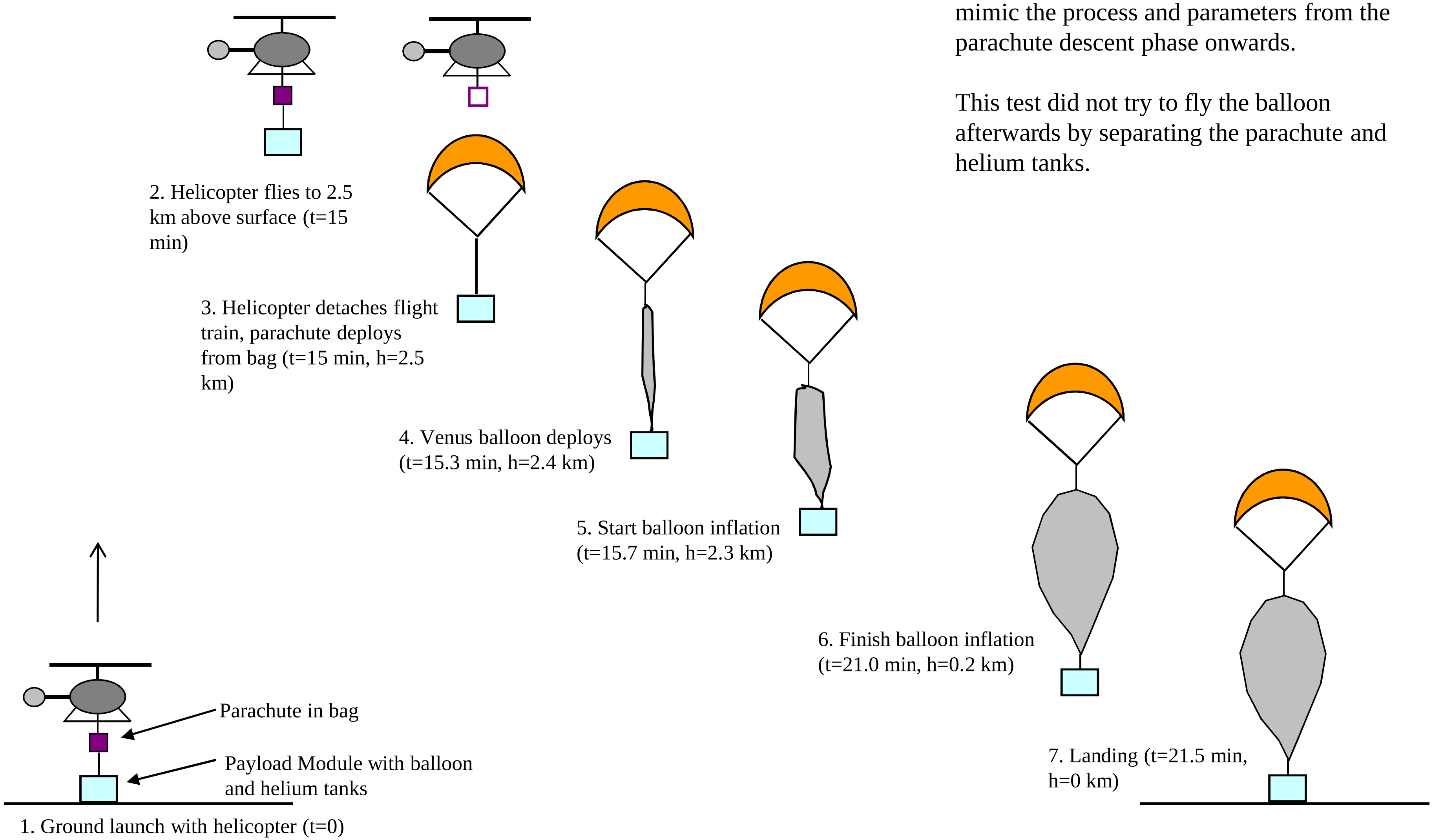


Graphic courtesy of T. Balint, JPL.

Aerial Deployment Flight Test Schematic

The flight test experiment was intended to mimic the process and parameters from the parachute descent phase onwards.

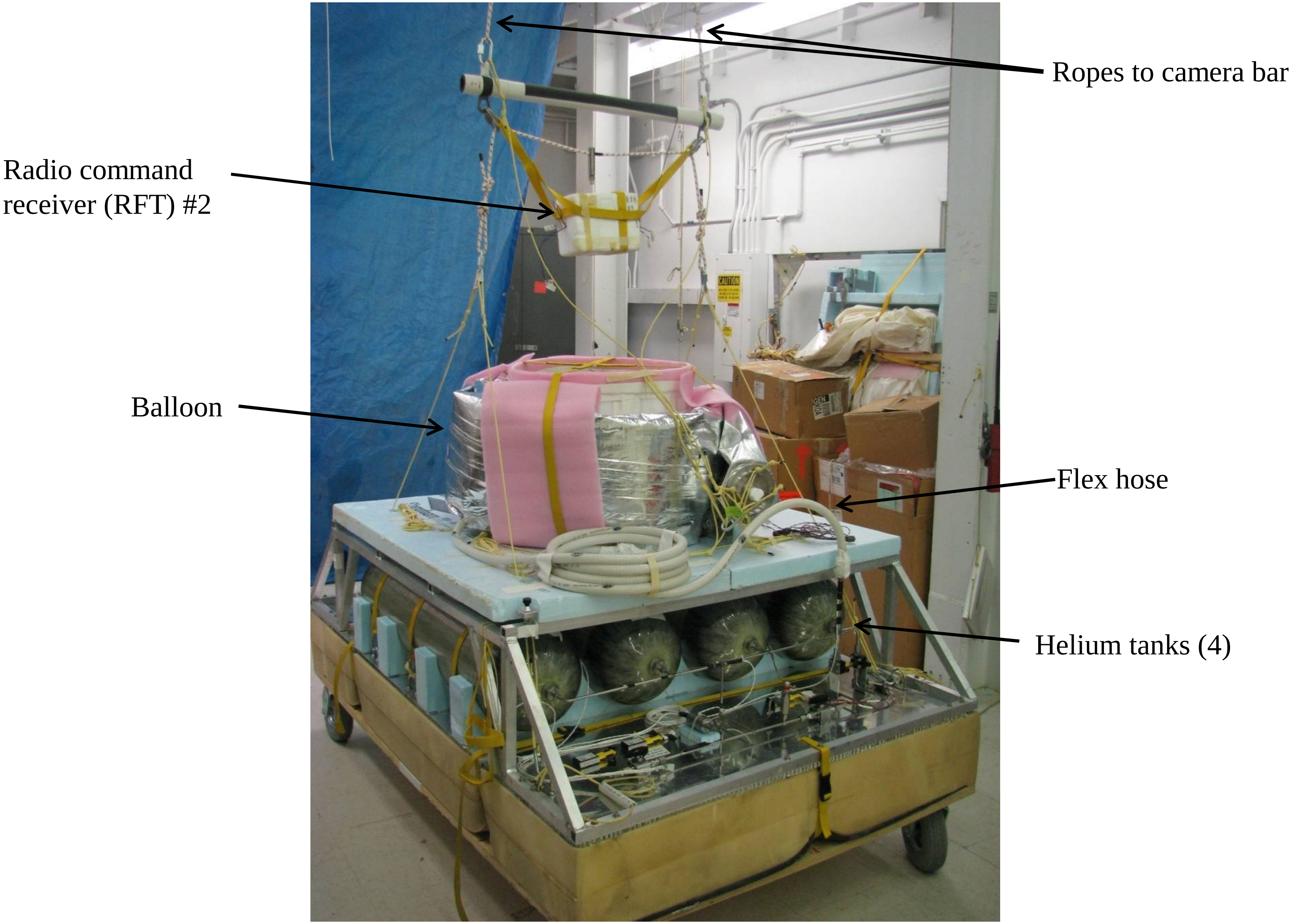
This test did not try to fly the balloon afterwards by separating the parachute and helium tanks.



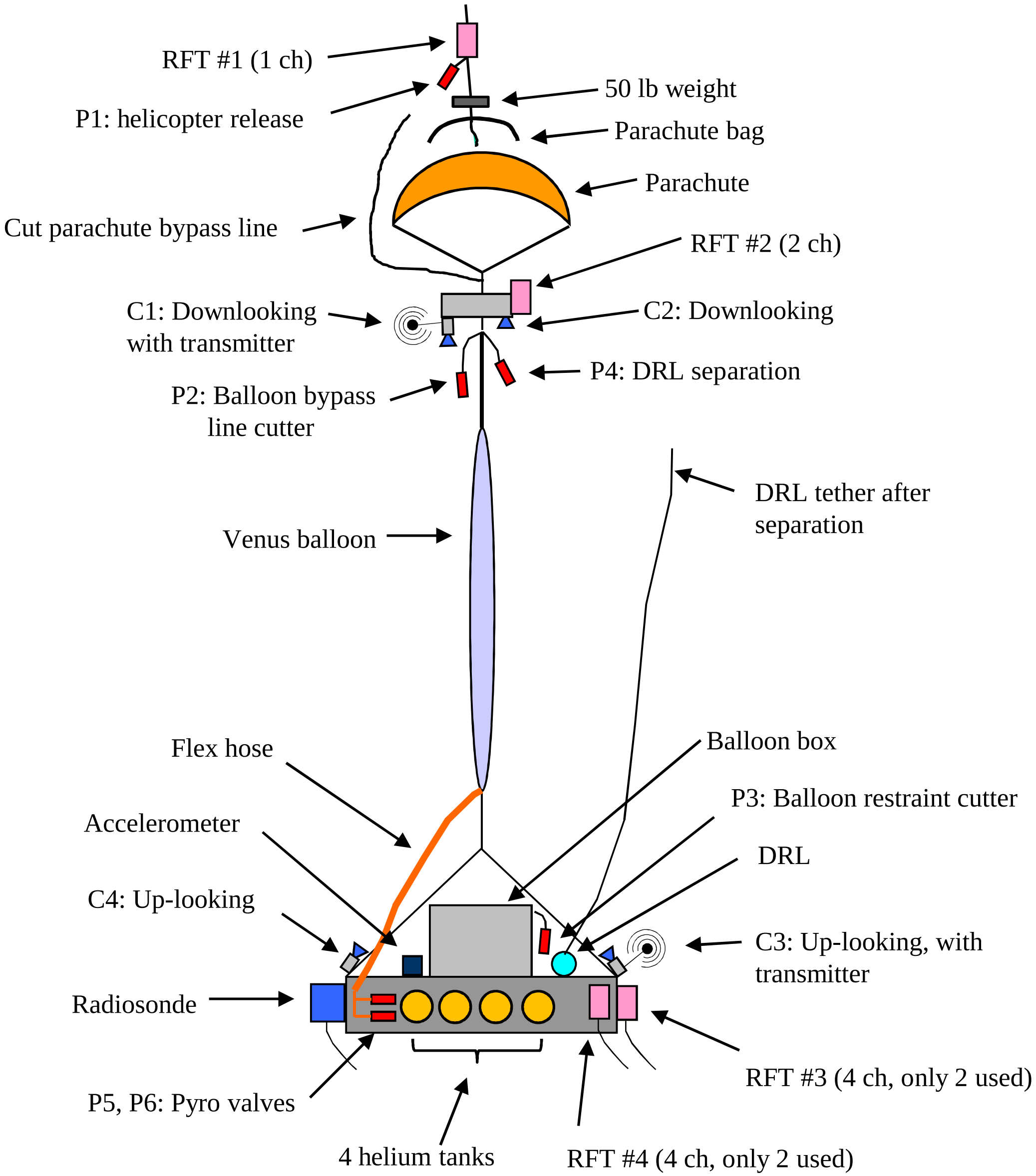
Test Team

- l-r: Gerry Walsh, Jeffery L. Hall, Joe Melko, Alexis Benz, Eric Kulczycki, Viktor Kerzhanovich, Mike Pauken, Scott Nash
- Not shown: Dick Hart, Dave Gibbs from National Helicopter Services company

Payload Module



Instrumentation and Pyro Schematic



There are 6 pyro devices:
- 4 cutters (P1, P2, P3 and P4)
- 2 valves (P5, P6)

There are 4 cameras, 2 downlooking (C1, C2) and 2 uplooking (C3, C4). C1 and C3 transmit in real time, C2 and C4 are camcorders that only record.

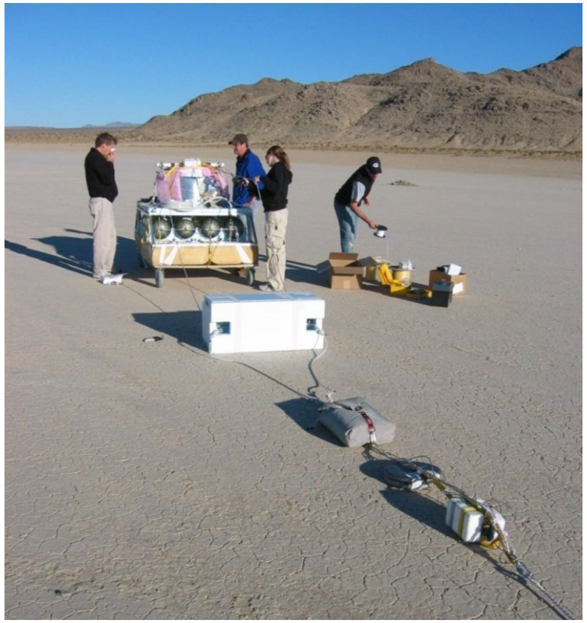
There is a Sippican radiosonde transmitting data:
- GPS location and velocity
- Atmos. temp and pressure
- Helium tank temp and pressure

There is a self-contained accelerometer mounted on the payload module.

There are 4 RFT boxes to fire the pyro devices:

RFT #1: Helicopter release
RFT #2: Balloon restraint cutter
Balloon bypass line cutter
DRL separation
RFT #3: Pyro valve 1
Pyro valve 2
RFT #4: Pyro valve 1
Pyro valve 2
(redundant with RFT #3)

Pre-flight Preparations



Flight Test Movie

Conclusions

- Results have been presented on recent technology development advances for a Venus balloon intended to fly in the mid-cloud layer, 55.5 km.
- A combined experimental and finite element analysis investigation was conducted to quantify the stress concentration factor at the weakest point of the balloon, the metal fitting to fabric end cap junction.
  - A stress concentration factor of 1.56 was determined.
- A successful aerial deployment and inflation test was conducted using a 5.5 m diameter balloon dropped from a 2.5 km altitude via a helicopter.
  - The balloon deployed and 7 kg of helium gas was injected as planned.
  - The balloon did not suffer any detectable damage from the deployment and inflation test.
- Collectively, these tests build confidence that the balloon technology is ready to support a new mission to Venus.